Planet Formation

Jack J. Lissauer *NASA Ames*

Observations

- Our Solar System
- Circumstellar disks

Theory

- General picture
- Growth of solid bodies
- Giant planet atmospheres

Extrasolar Planets

- Observational techniques
- Data
- Formation models

Conclusions:

Diversity of Plausible Planetary Systems

Our Solar System

Dynamics

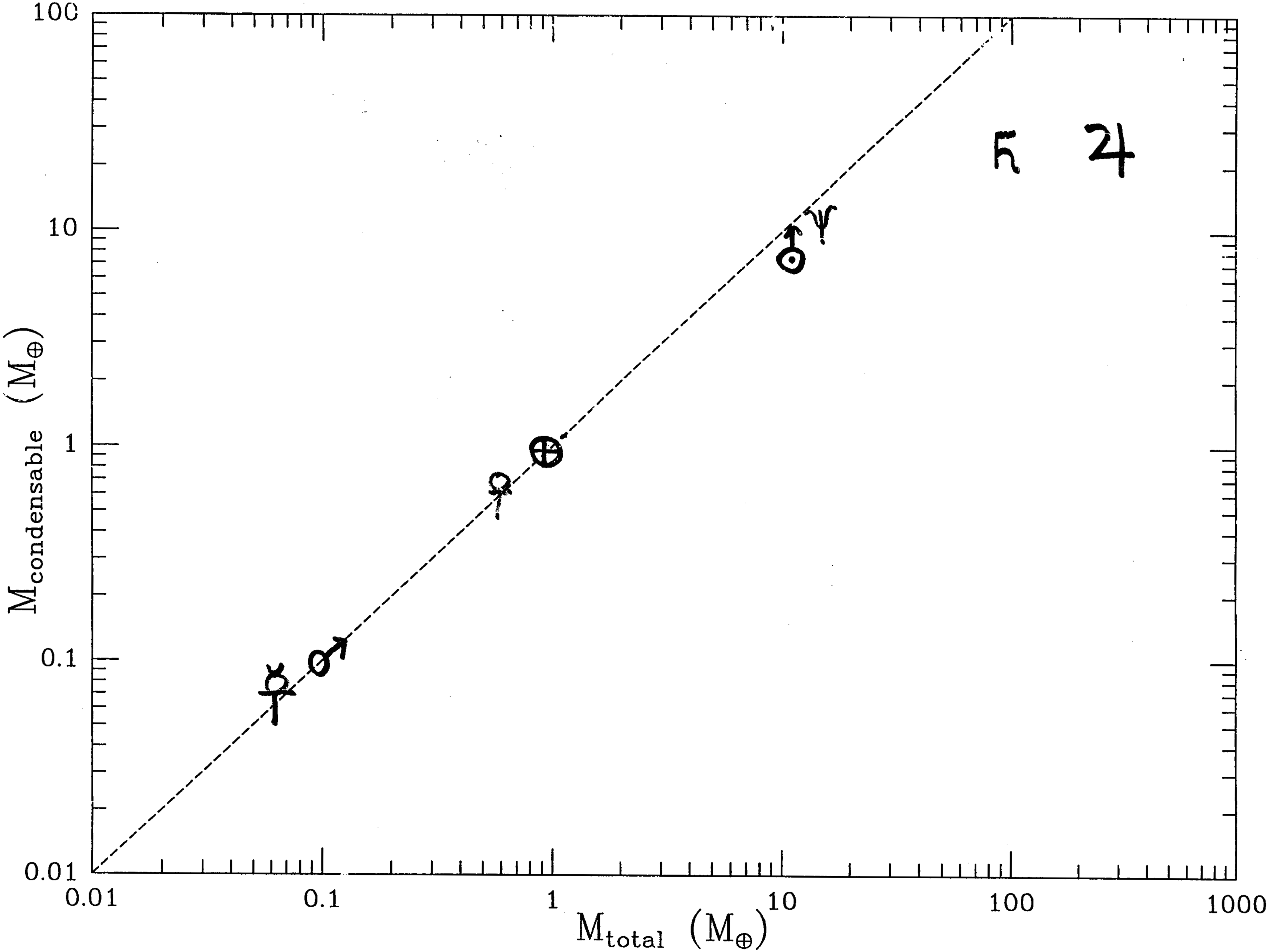
Planetary orbits nearly circular & coplanar
Spacing increases with distance from Sun
All giant planets have satellite systems
Planetary rings
Planets rotate rapidly unless tidally slowed

Composition

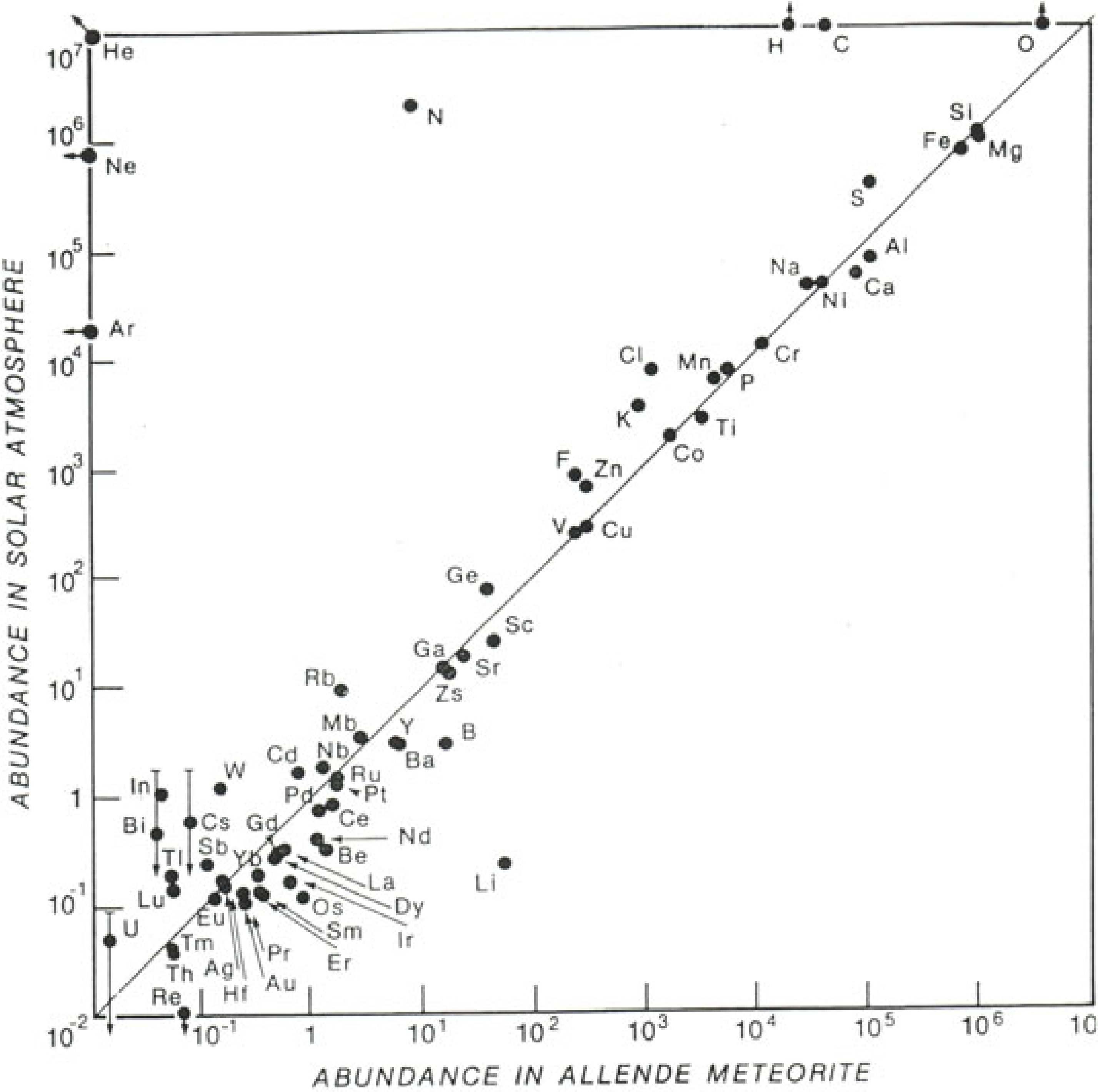
Largest bodies most gas-rich
Rocky bodies near Sun, icy bodies farther out
Elemental/isotopic abundances similar (ex. volatiles)
Meteorites -- active heterogeneous environment

Planetary 'Geology'

Cratering record implies far more small bodies
in first 800 million years than at present



100
10
1
0.1
0.01
0.01
0.1
1
10
100
1000
$M_{condensable}$ $(M_\oplus)$
M_{total} $(M_\oplus)$


ABUNDANCE IN SOLAR ATMOSPHERE
ABUNDANCE IN ALLENDE METEORITE
10^7
10^6
10^5
10^4
10^3
10^2
10^1
1
10^-1
10^-2
10^-1
1
10^1
10^2
10^3
10^4
10^5
10^6
10
He
H
C
O
N
Ne
Si
Fe
Mg
S
Al
Na
Ca
Ni
Ar
Cl
Mn
Cr
P
K
Ti
Co
F
Zn
V
Cu
Ge
Sc
Ga
Sr
Rb
Zs
Mb
Y
B
Ba
Cd
Nb
Ru
W
Pt
In
Pd
Ce
Bi
Cs
Gd
Nd
Tl
Sb
Yb
Be
La
Li
Lu
Dy
Eu
Os
U
Ir
Sm
Tm
Pr
Ag
Er
Th
Hf
Au
Re

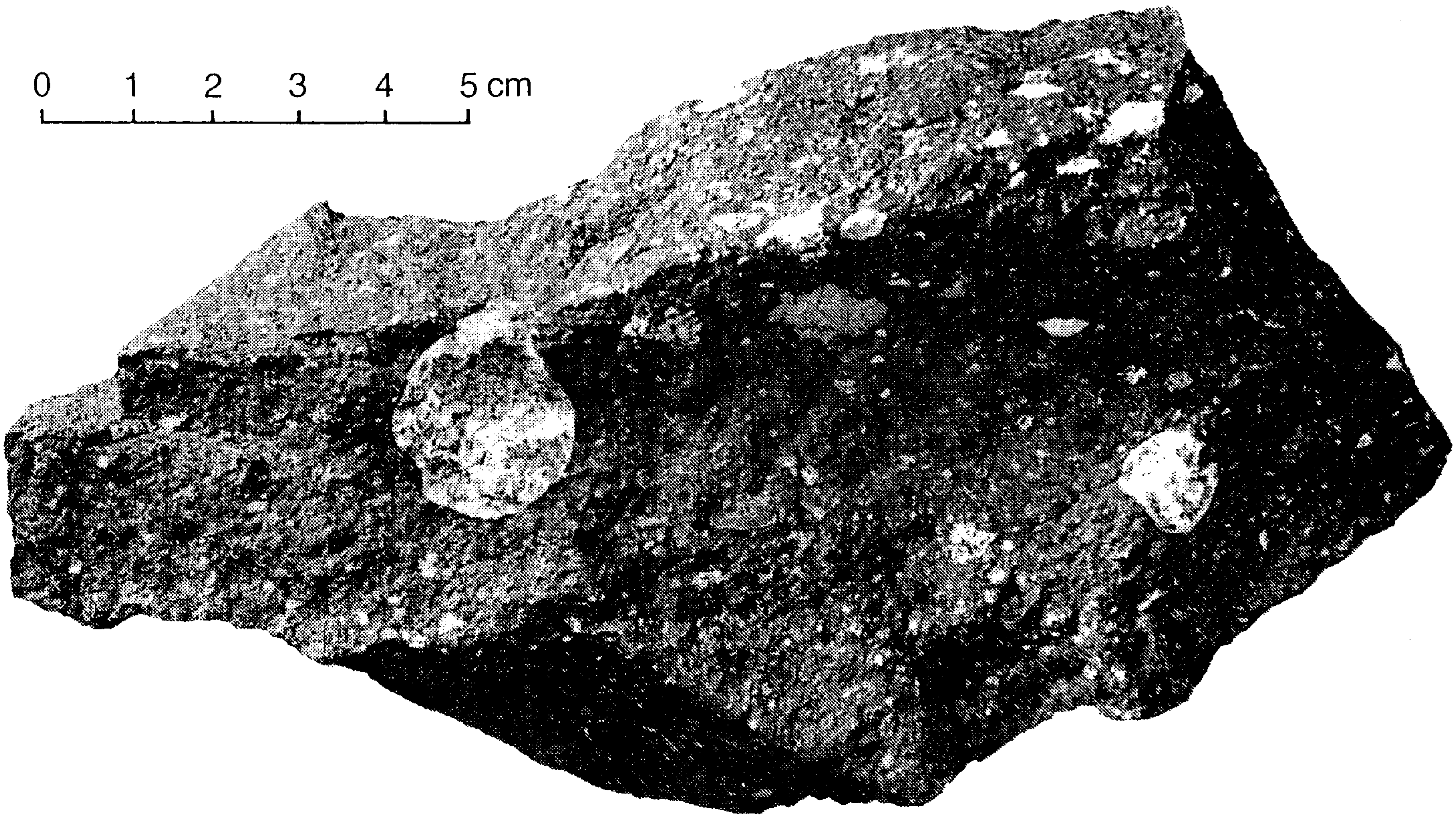
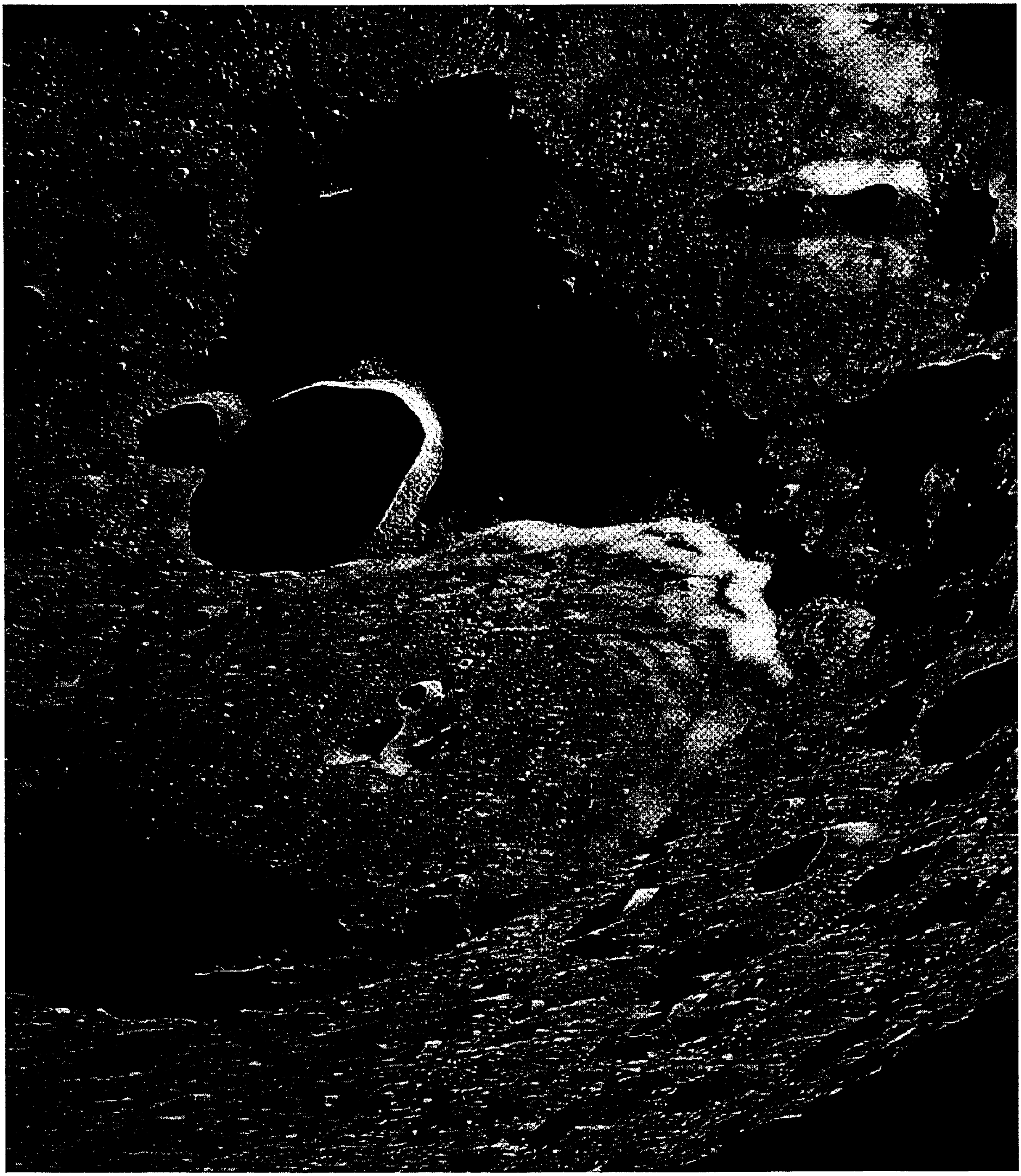
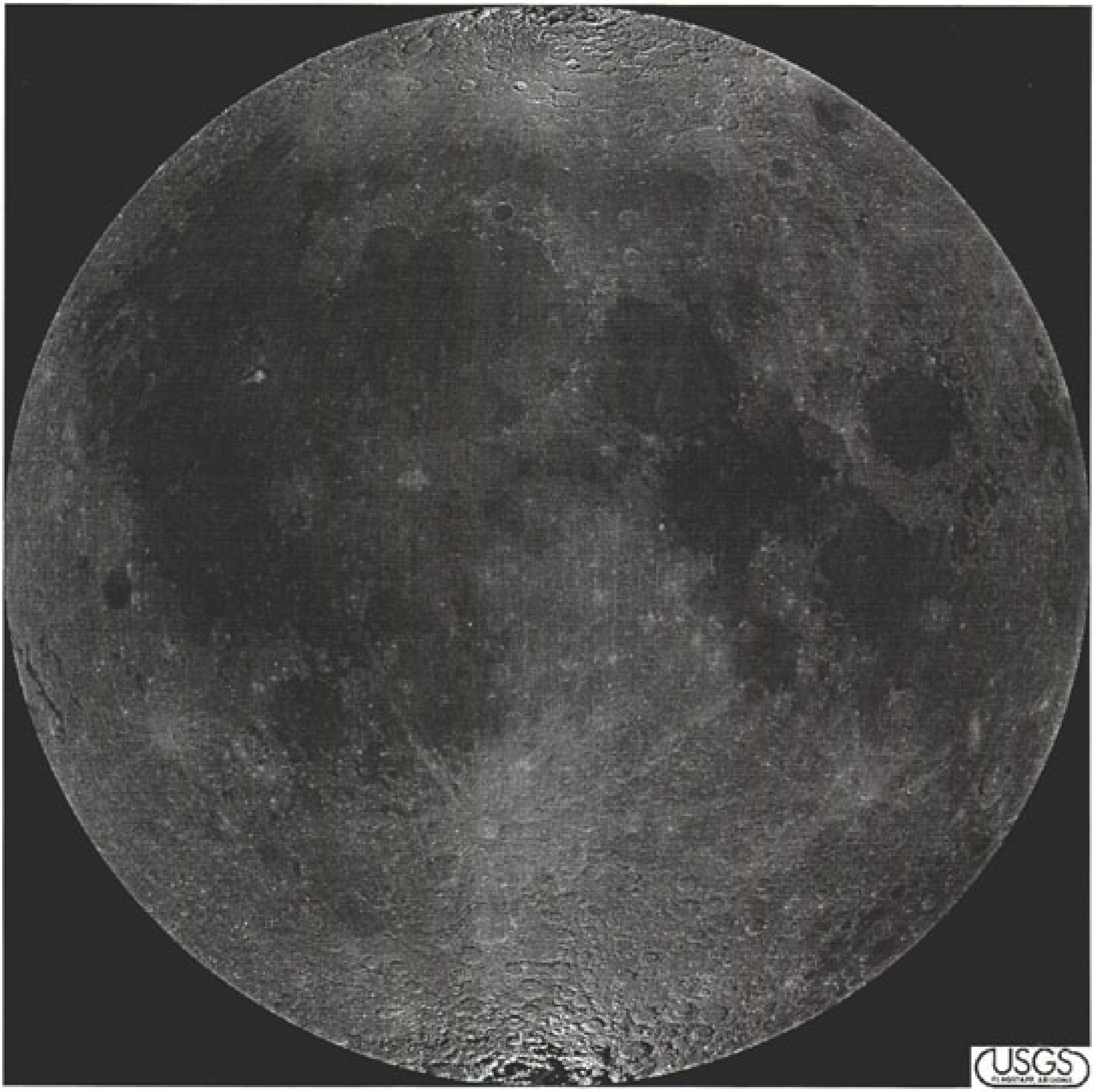


Figure VIII-4. Fractured surface of the Allende CV chondrite showing light-colored refractory inclusions set in a dark-gray matrix. The two large, round inclusions show the typical shapes of the coarse-grained inclusions; fine-grained inclusions show more irregular shapes. At 2.5 cm, the larger round inclusion is the largest ever observed in a CV chondrite. Note the parallel orientation of the long axes of some of the smaller white inclusions. (Photo from R. S. Clarke et al., *Smithson. Contrib. Earth Sci.* 5:1, 1970.)




USGS

Disks Around Young Stars

<u>Observational Evidence</u>

Images

Rotation curves

Infrared excesses

<u>Disk Properties</u>

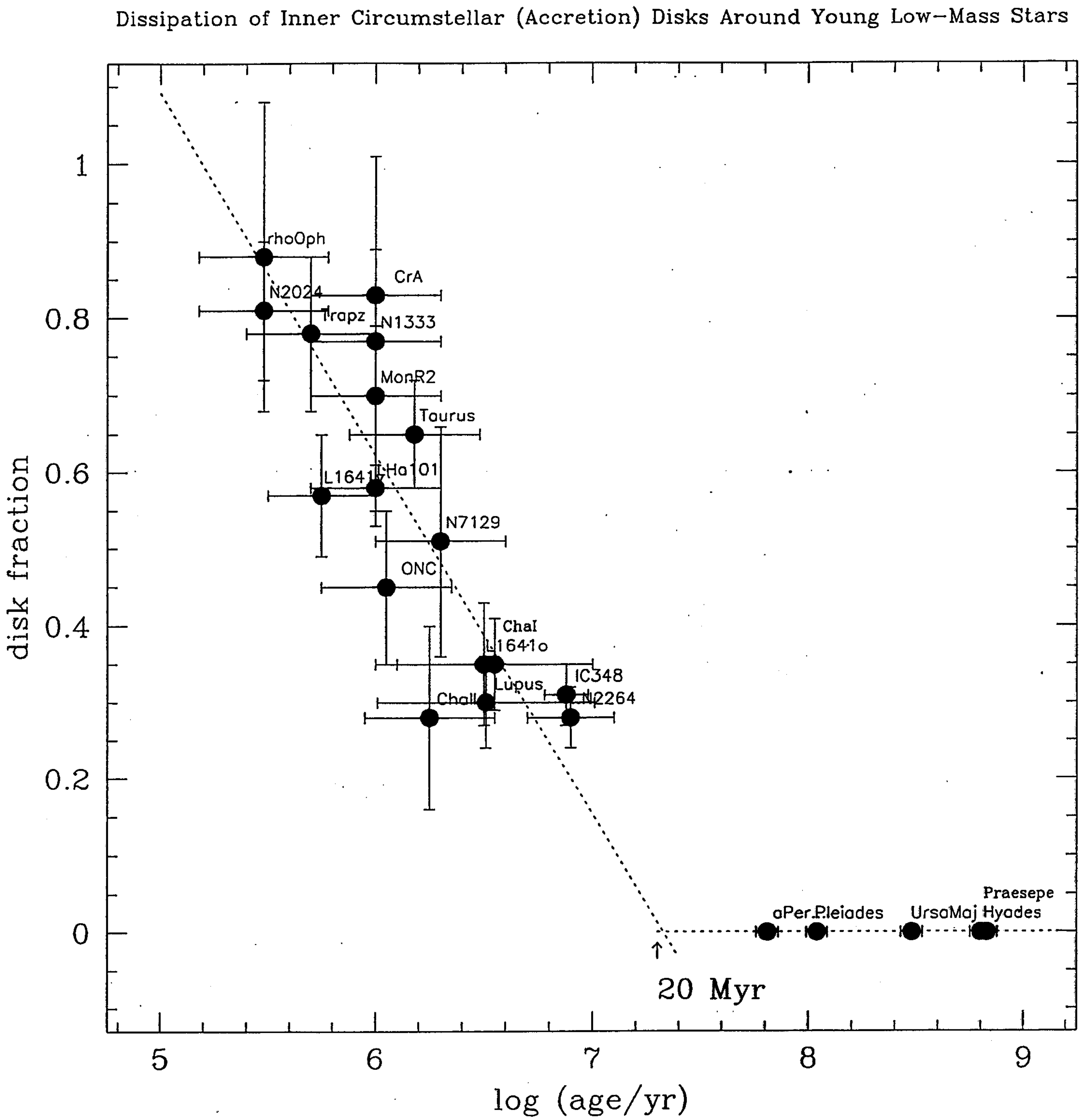
$r > 40$ AU [uncertain]

$M \sim 0.001 - 1\ M_\odot$ [very uncertain]

Lifetime (dust) < 10 MY [varies star to star]

Low mass disks ($\ll M_\oplus$) detected around many older stars

Hillenbrand (1999)



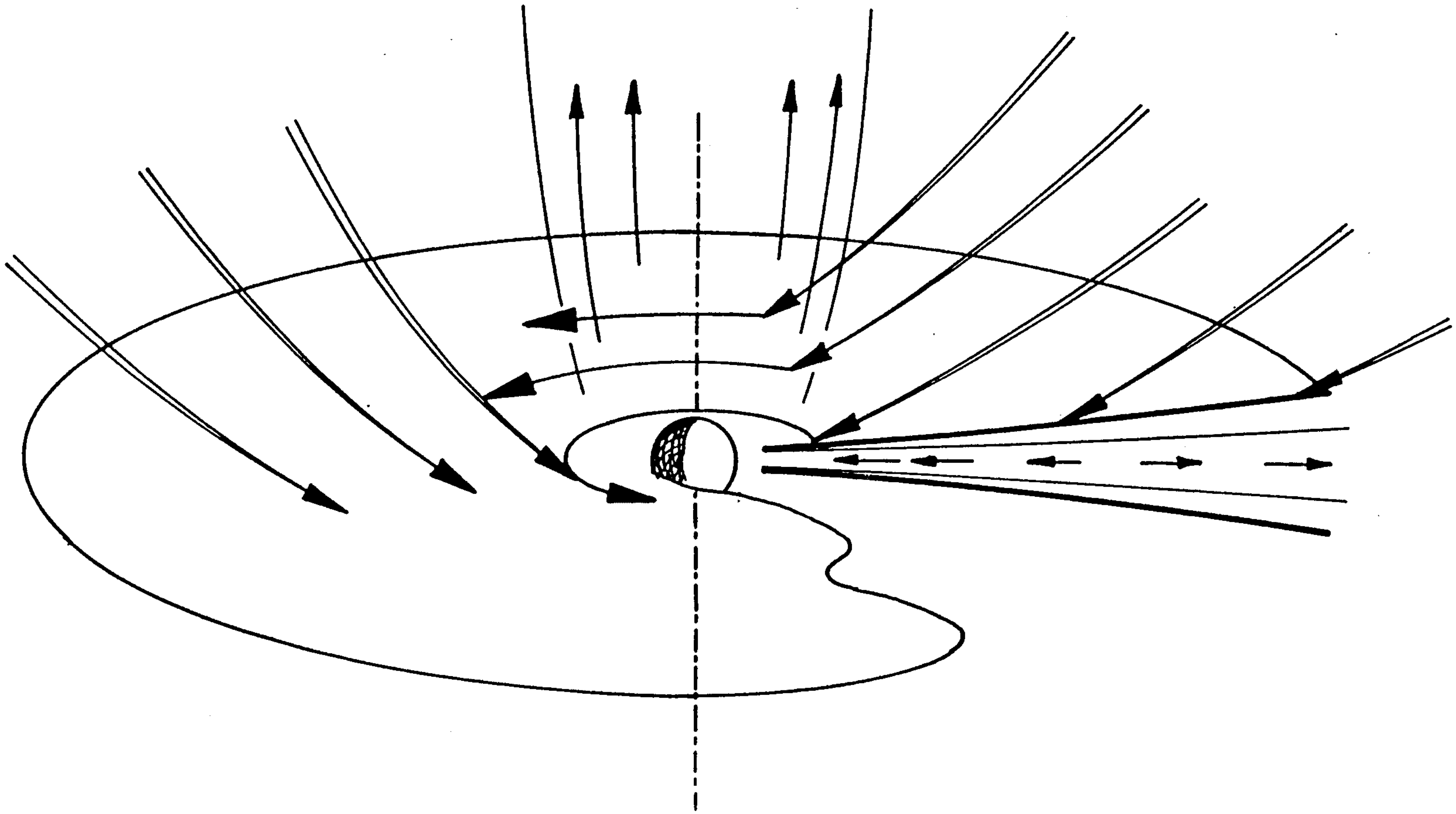
Solar Nebula Theory

(Kant 1755, Laplace 1796)

The Planets Formed in a Disk in Orbit About the Sun

- Explains near coplanarity and circularity of planetary orbits
- **Disks are believed to form around most young stars**
  - ♂ Theory: Collapse of rotating molecular cloud core
  - ♀ Observations: Proplyds, β Pic, IR spectra of young stars
- Predicts planets to be common, at least about single stars

Protoplanetary Disk

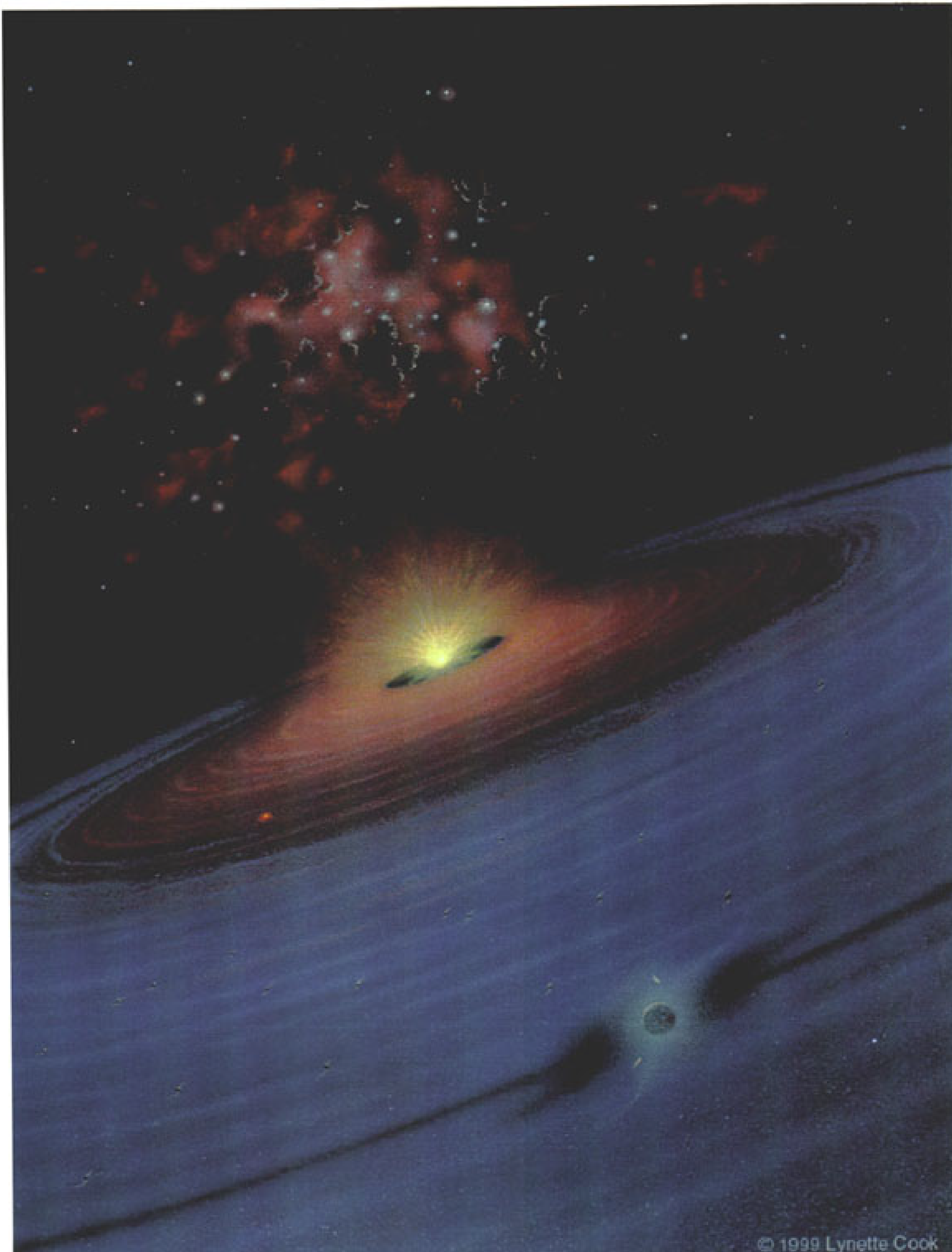


P. Cassen

Planetesimal Hypothesis

Planets Grow via Binary Accretion of Solid Bodies,
Massive Giant Planets Gravitationally Trap
H_2 + He Atmospheres

- **Explains planetary composition vs. mass**
- **General; for planets, asteroids, comets, moons, etc.**
- **Can account for Solar System; predicts diversity**



Stages of Planetary Growth

1) Planetesimal Formation

- Dust to kilometer-size bodies: gas affects
- Settling, sticking, gravitational instabilities?

2) Runaway Growth

- Binary collisions, planetesimal scattering
- Gravity → largest bodies accrete most rapidly

3) Merger of Planetary Embryos

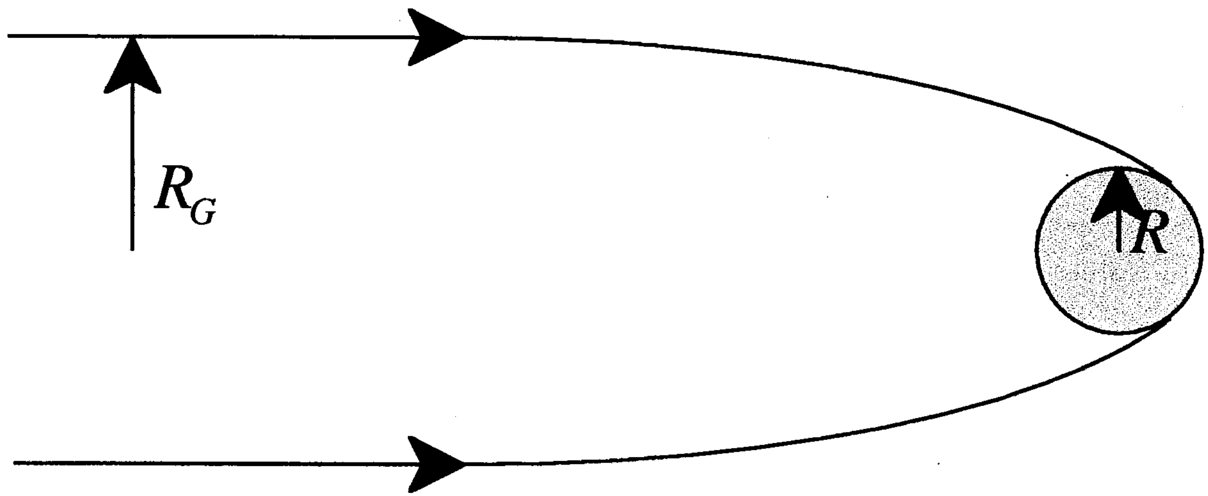
- High-velocity, stochastic
- Slow, nebula may dissipate

4) Accretion of Gas

- Requires massive planetary embryos
- Interacts with stages (2) & (3)
- Termination and mass loss uncertain

Collision Cross-Sections

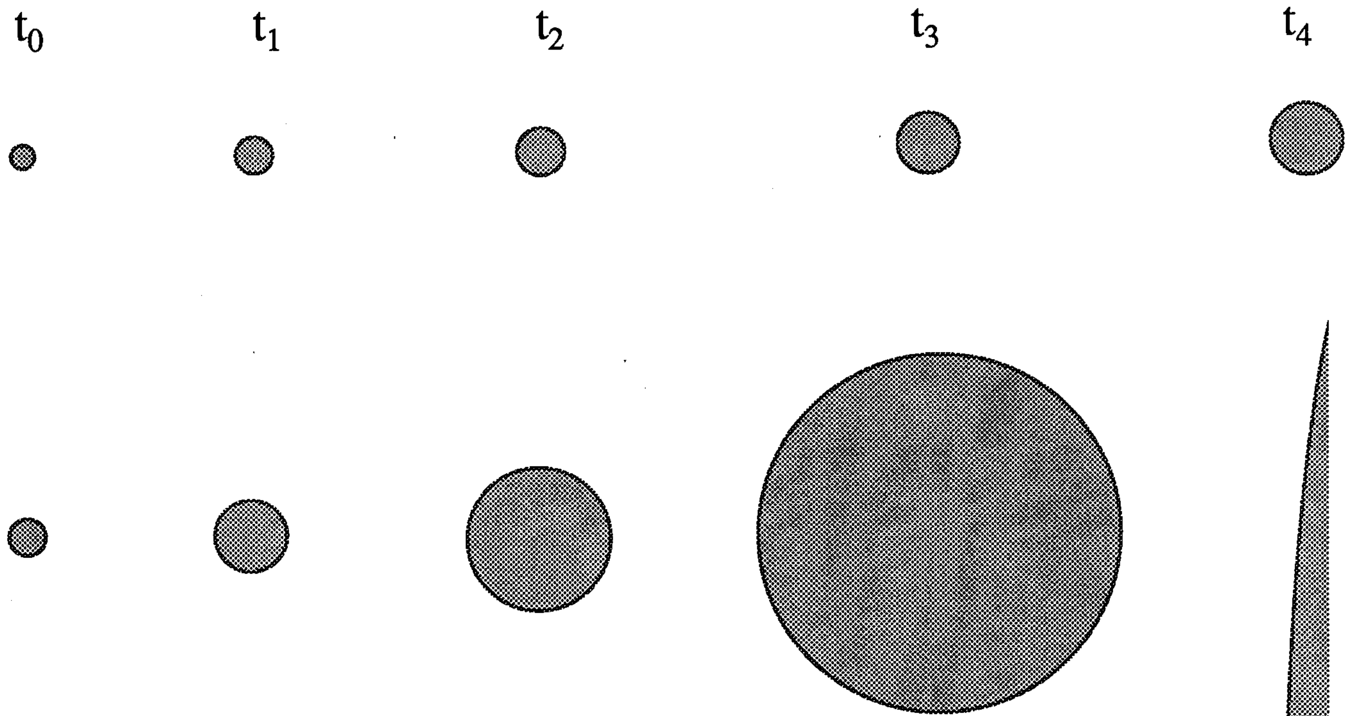
Planet's gravity enhances collision rate
Neglect star's gravity: 2+2-body approx.

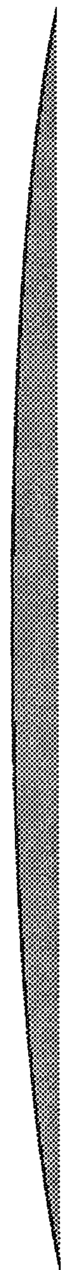


Assume impacts → accretion

$$\frac{dM}{dt} = \pi R_G^2 \rho v = \pi R^2 \rho v \{1 + (\tfrac{v_e}{v})^2\}$$

Runaway Growth





$$\frac{dR}{dt} = \frac{1}{3R^2}\frac{3}{4\pi\rho_p}\frac{dM}{dt} = \frac{\sigma\Omega}{4\rho_p}\left(1 + \frac{\frac{4}{3}\pi G\rho_p R^2}{v^2}\right)$$

For $v_e >> v$, $\quad \dfrac{dR}{dt} \propto R^2$

End of Runaway Growth

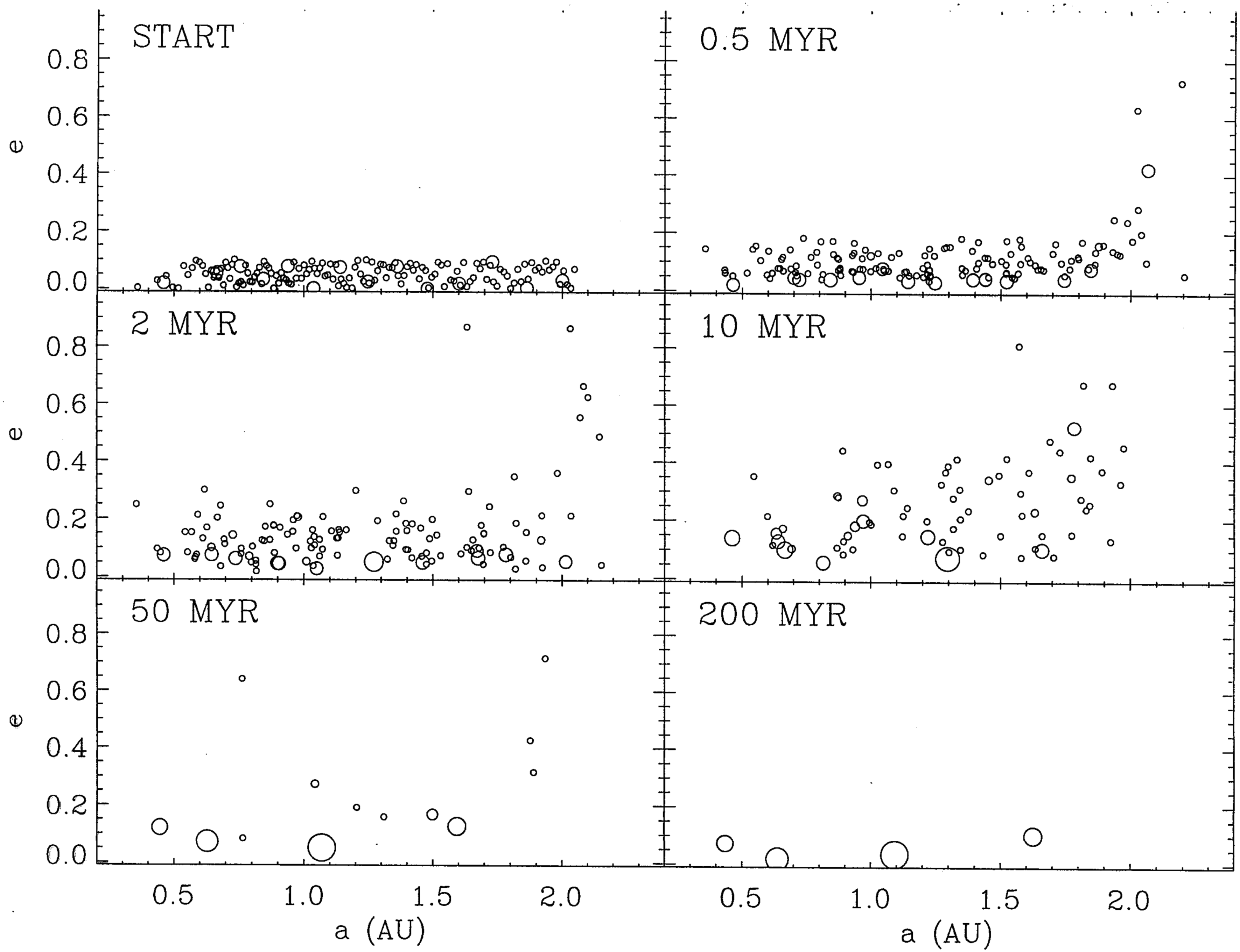
✓ Requirements for runaway

- *Nearby solid material*
- *Low relative velocities*

Post-runaway growth

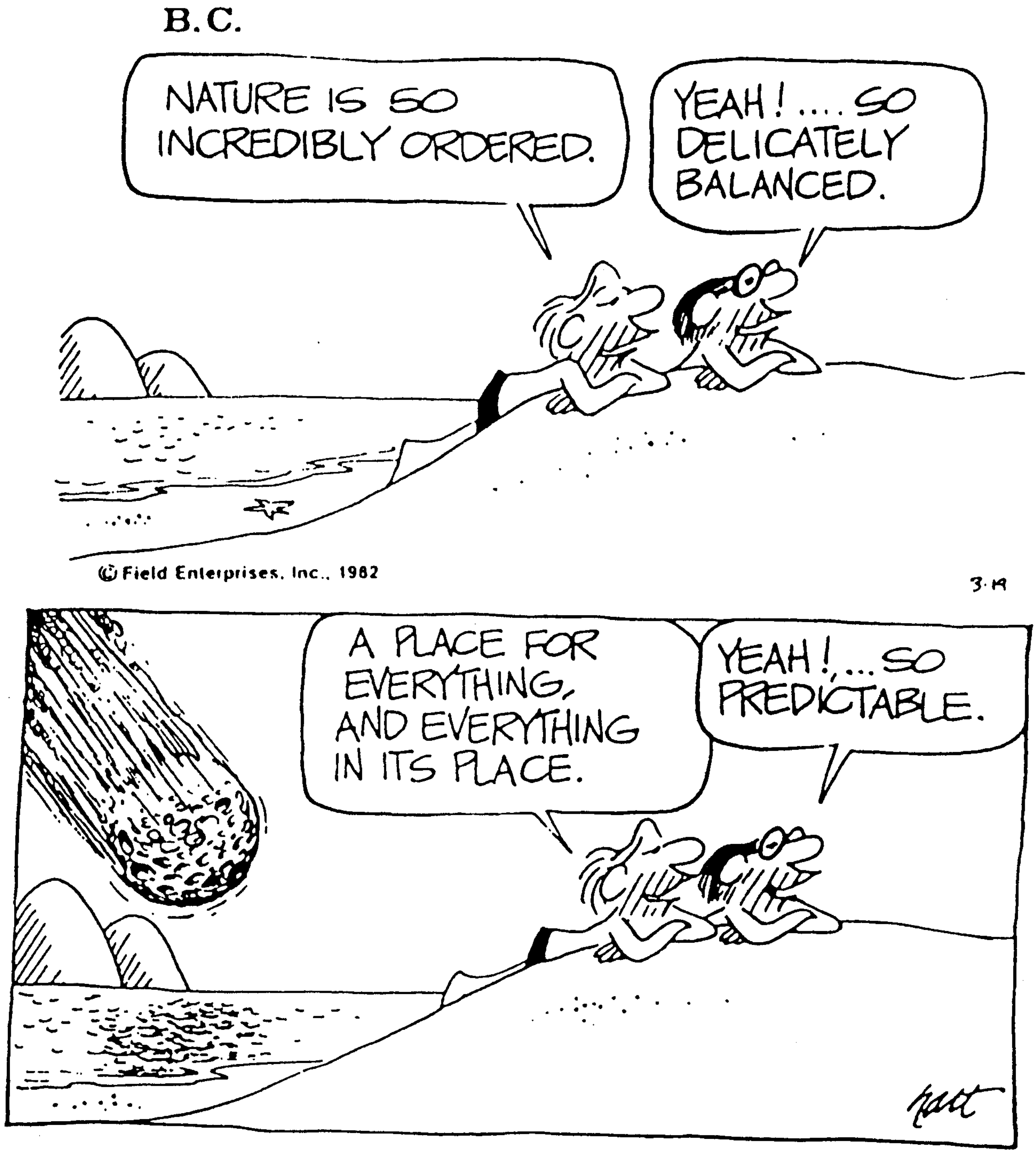
- *Migrating solid material*
- *High-velocity solids*
- *Gas*

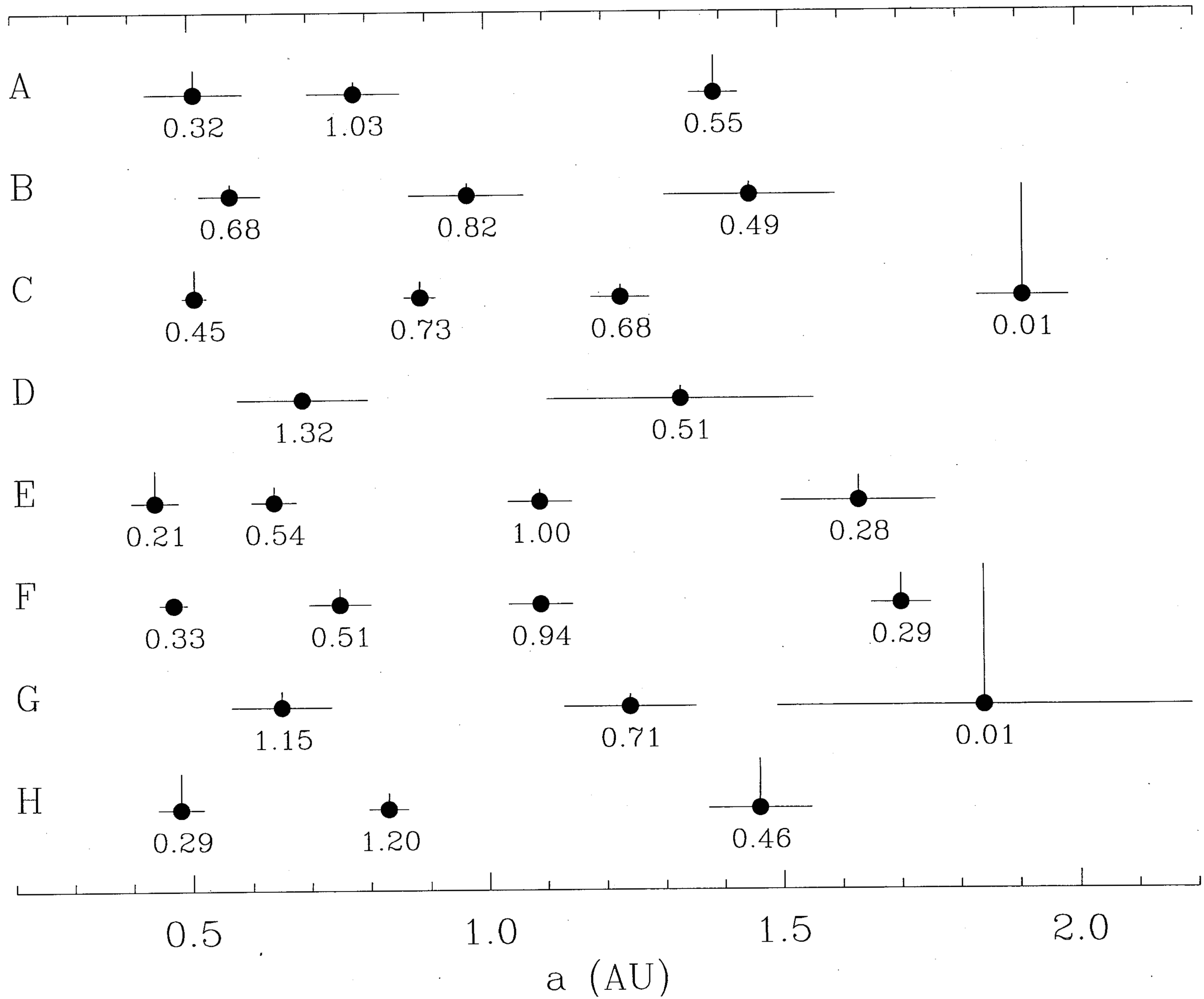
Terrestrial Planet Growth



J. E. Chambers

Bull's-Eye


B.C.
NATURE IS SO INCREDIBLY ORDERED.
YEAH! .... SO DELICATELY BALANCED.
© Field Enterprises, Inc., 1982
3-19
A PLACE FOR EVERYTHING, AND EVERYTHING IN ITS PLACE.
YEAH! ... SO PREDICTABLE.
hart


A
0.32
1.03
0.55
B
0.68
0.82
0.49
C
0.45
0.73
0.68
0.01
D
1.32
0.51
E
0.21
0.54
1.00
0.28
F
0.33
0.51
0.94
0.29
G
1.15
0.71
0.01
H
0.29
1.20
0.46
0.5
1.0
1.5
2.0
a (AU)

Giant Planet Formation

1-D (spherical) models; solids and gas accreted; accretion/contraction provide energy; energy loss allows contraction & gas accretion

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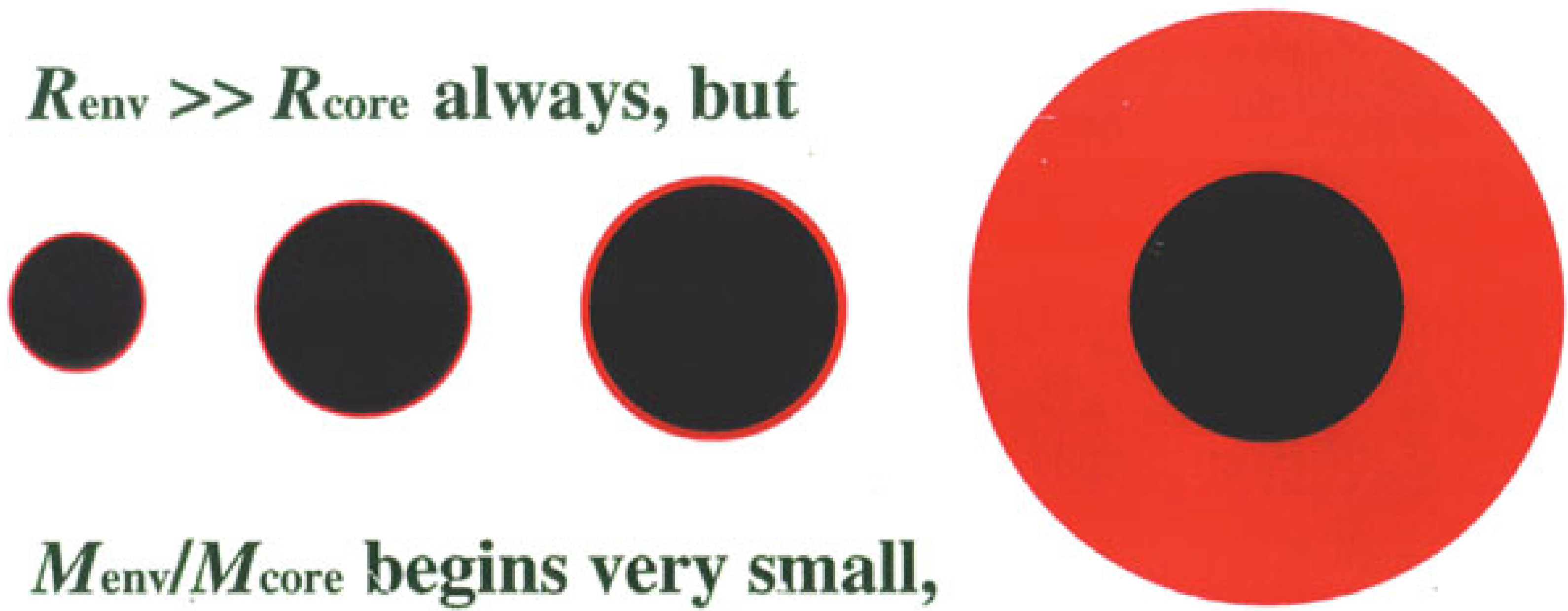
$R_{env} >> R_{core}$ always, but



M_{env}/M_{core} begins very small, increases; growth rapid when $M_{env} \geq M_{core}$

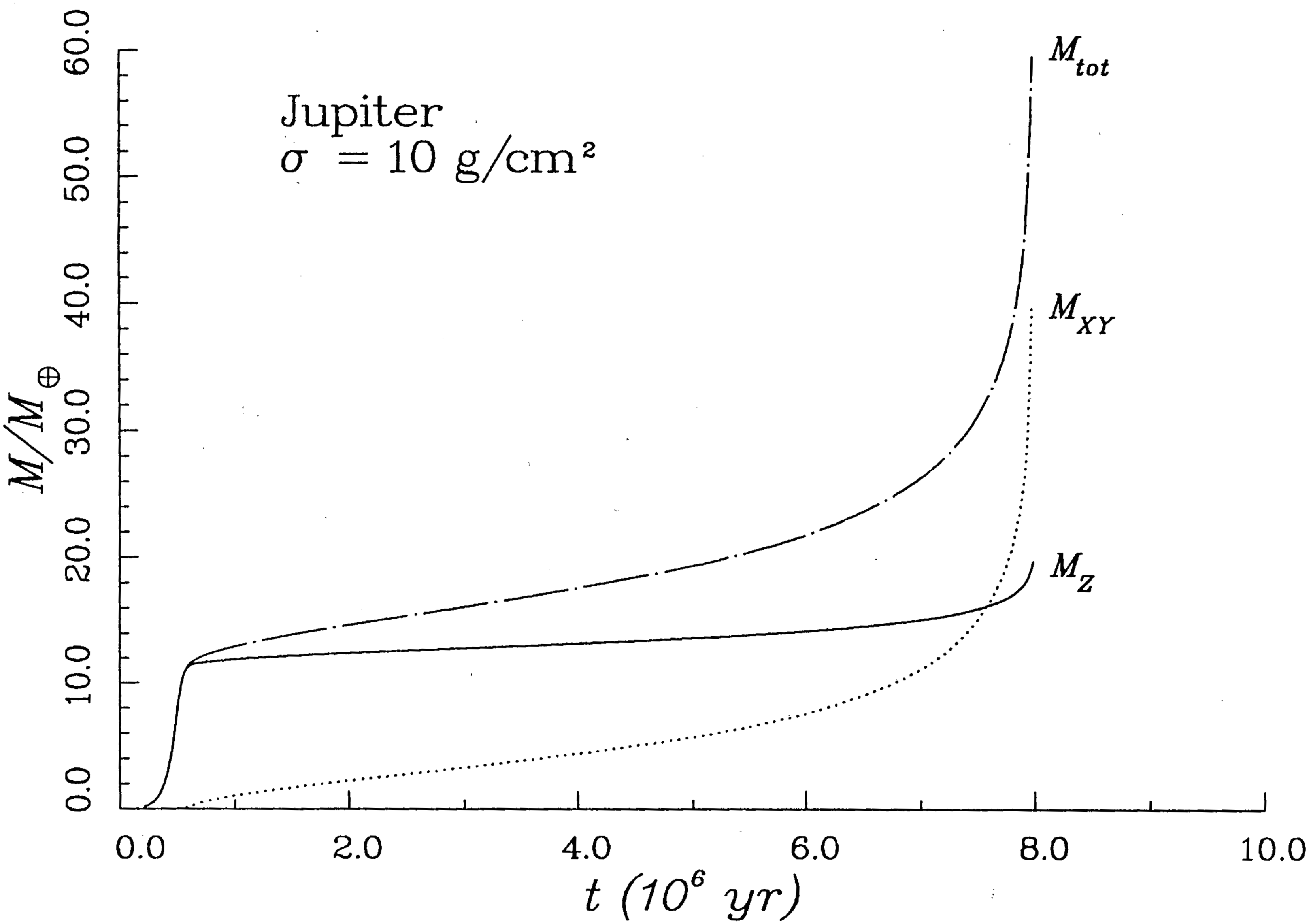
Approach

- Calculate gas and planetesimal accretion rates in an interactive self-consistent manner

- *Planetesimal Accretion*: Isolated embryo
  - Initially uniform planetesimal disk
  - 3-body accretion cross-section
  - No migration of planetesimals

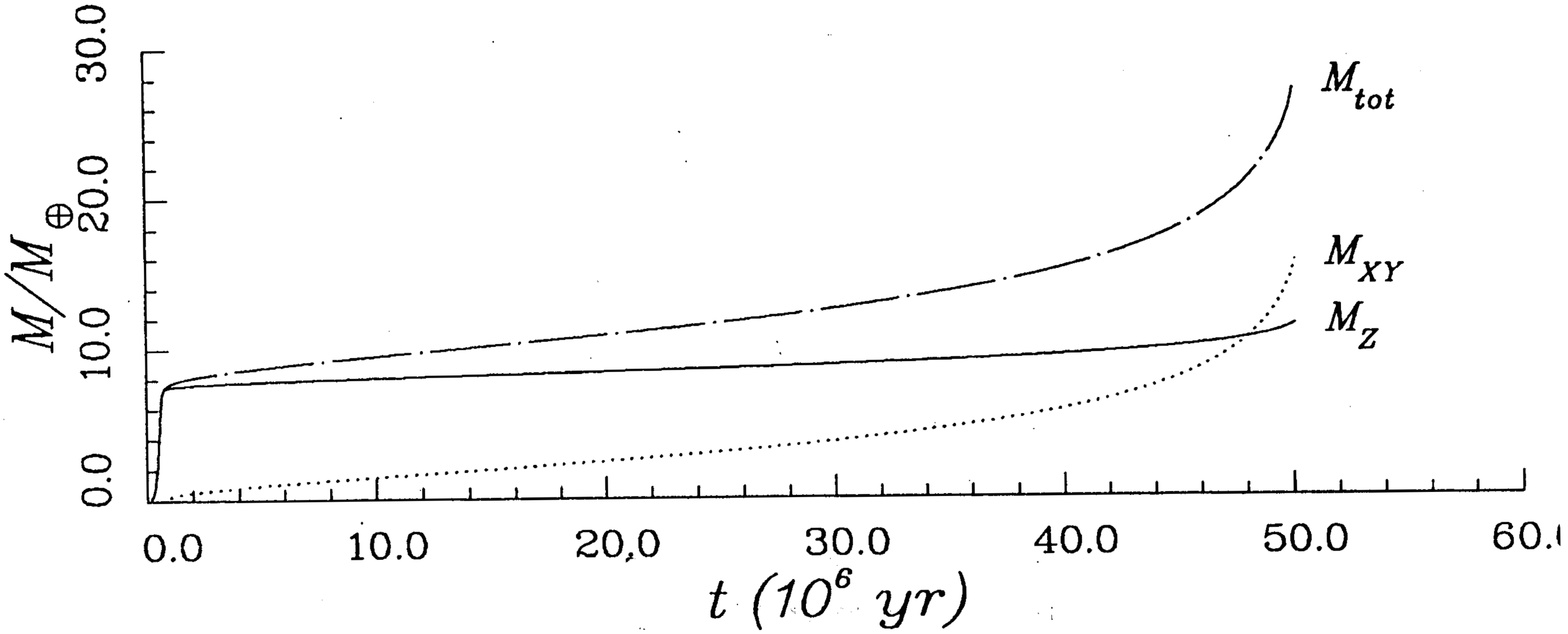
- Stellar evolution code for interior structure & evolution

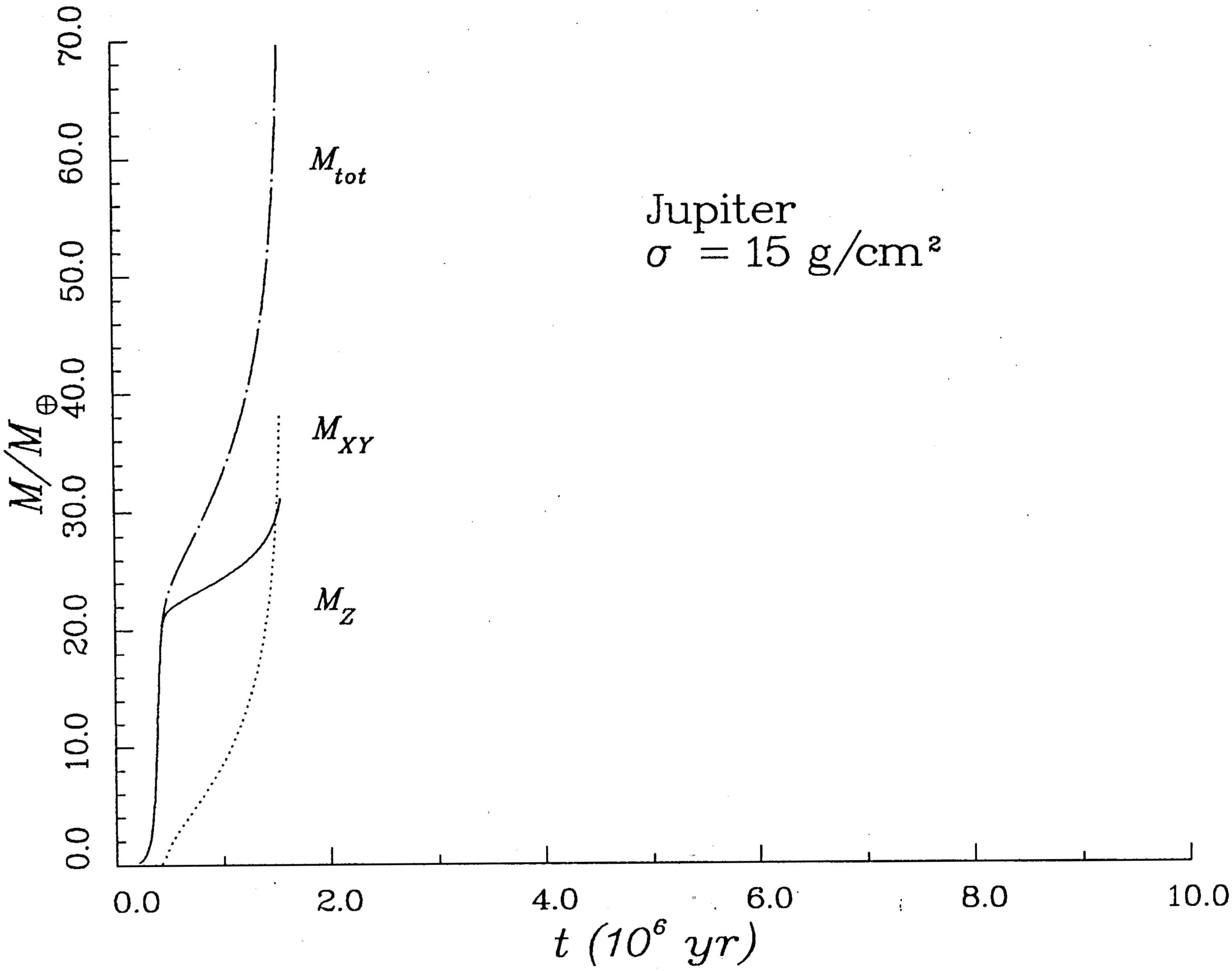
- *Gas Accretion* $\propto$ volume vacated by contracting envelope



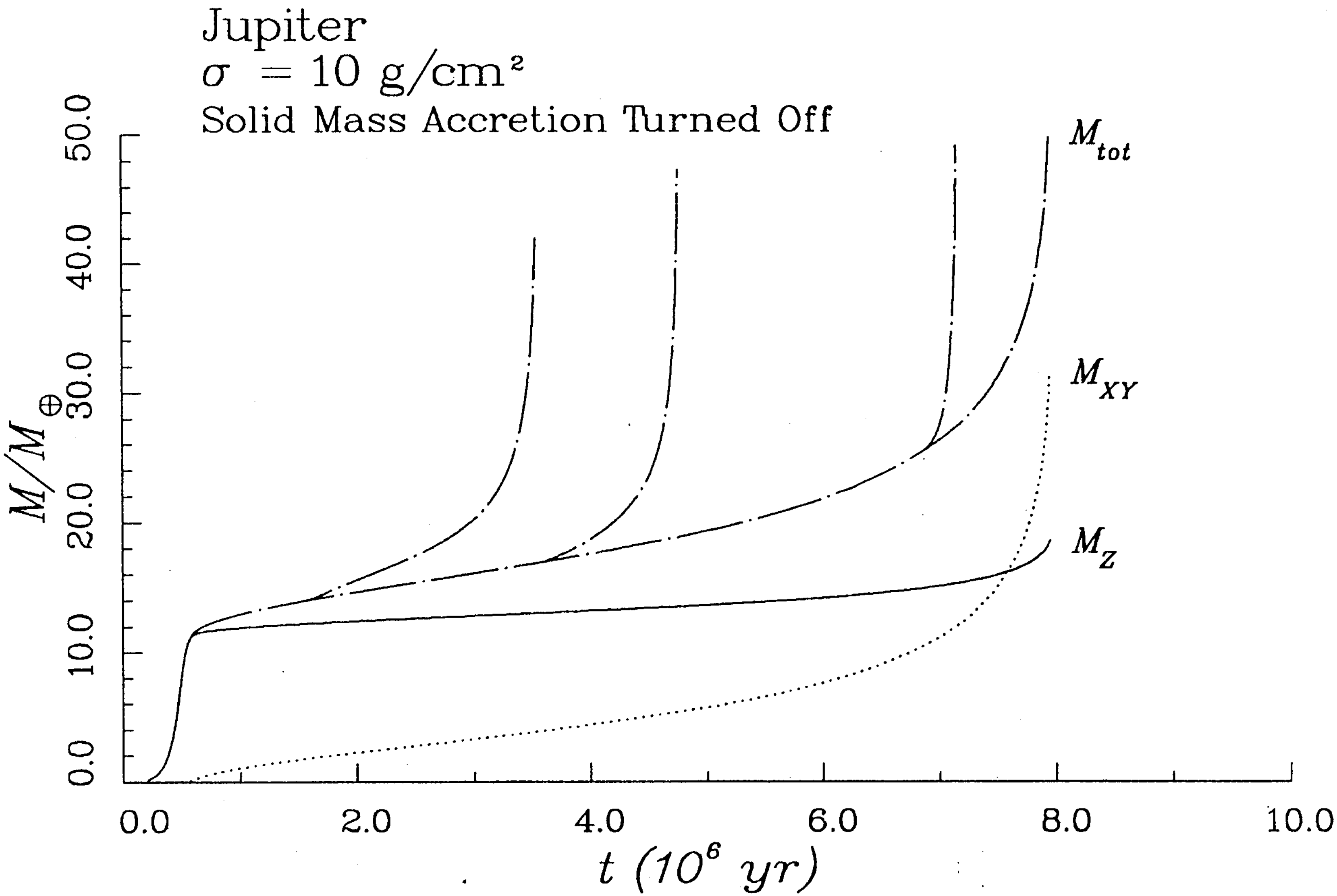
Jupiter
σ = 10 g/cm²
M_tot
M_XY
M_Z
M/M⊕
t (10⁶ yr)
0.0
10.0
20.0
30.0
40.0
50.0
60.0
0.0
2.0
4.0
6.0
8.0
10.0

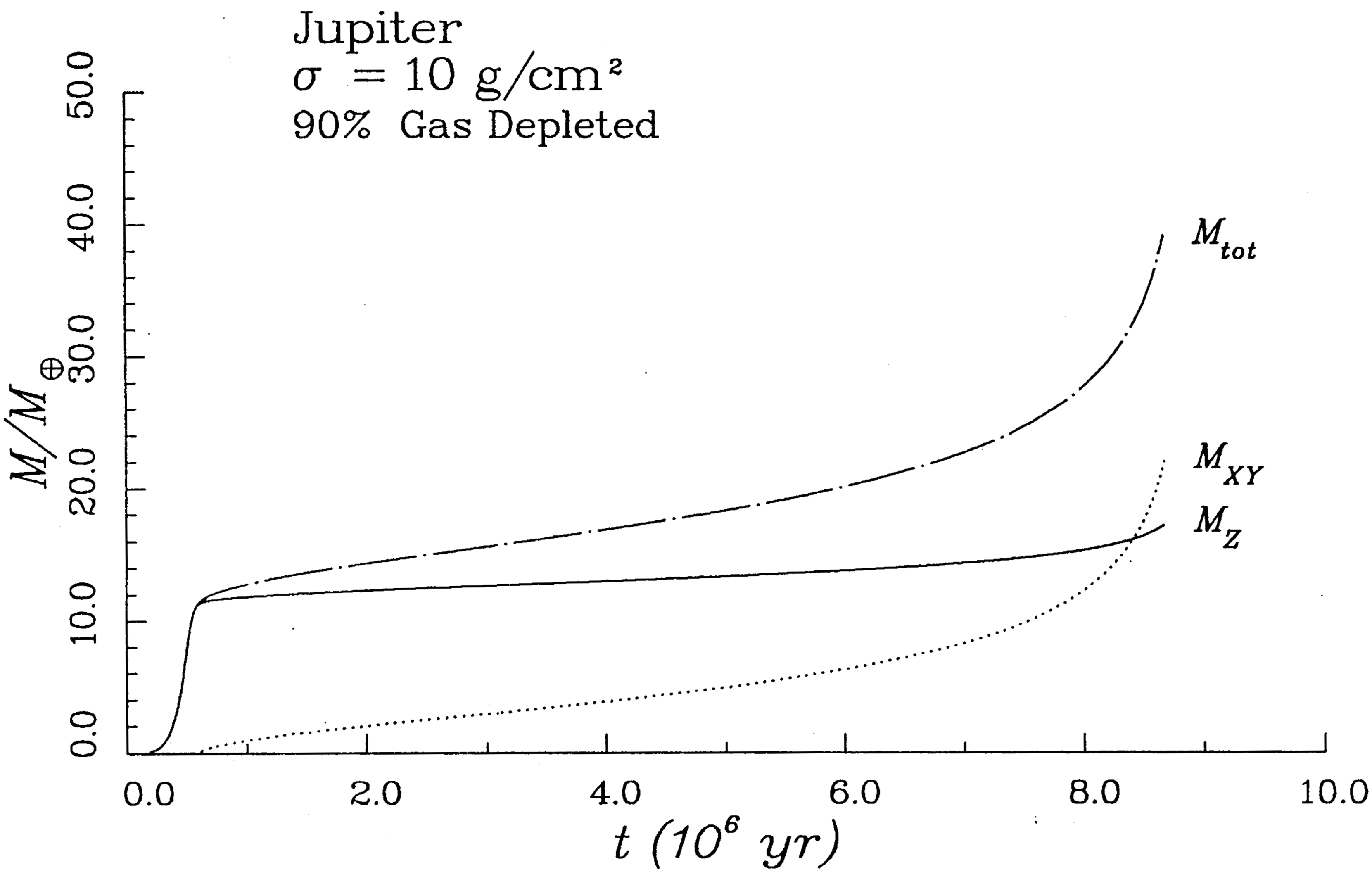
Jupiter
$\sigma = 7.5$ g/cm²





Jupiter
$\sigma = 15$ g/cm²
M_{tot}
M_{XY}
M_Z
$M/M_\oplus$
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
0.0
2.0
4.0
6.0
8.0
10.0
t (10^6 yr)


Jupiter
σ = 10 g/cm²
Solid Mass Accretion Turned Off
M_{tot}
M_{XY}
M_Z
$M/M_{\oplus}$
0.0
10.0
20.0
30.0
40.0
50.0
0.0
2.0
4.0
6.0
8.0
10.0
$t\ (10^6\ yr)$


Jupiter
$\sigma = 10$ g/cm²
90% Gas Depleted
M_{tot}
M_{XY}
M_Z
$M/M_\oplus$
0.0
10.0
20.0
30.0
40.0
50.0
0.0
2.0
4.0
6.0
8.0
10.0
t (10^6 yr)

Stages of Giant Planet Growth

Phase 1: Planetesimal Runaway

- Condensables dominate mass
- Gas fraction small, but increasing
- Ends when protoplanet isolated

Phase 2: Cooling and Contraction

- Gas mass increases gradually
  - Atmosphere hot from accretion
  - Limited by planet's ability to radiate energy
- Slow planetesimal accretion

Phase 3: Gas Runaway

- Envelope contraction rapid
  - Planet's gravity compresses atmosphere
  - Runaway, not free-fall collapse
- Gas mass increases very rapidly
- Planetesimal mass increases rapidly

Termination of Planetary Growth

I. Terrestrial-type Planets

Mergers &/or ejections until "stable" state reached

II. Jovian-type Planets

A. Rate of gas accretion is lesser of:

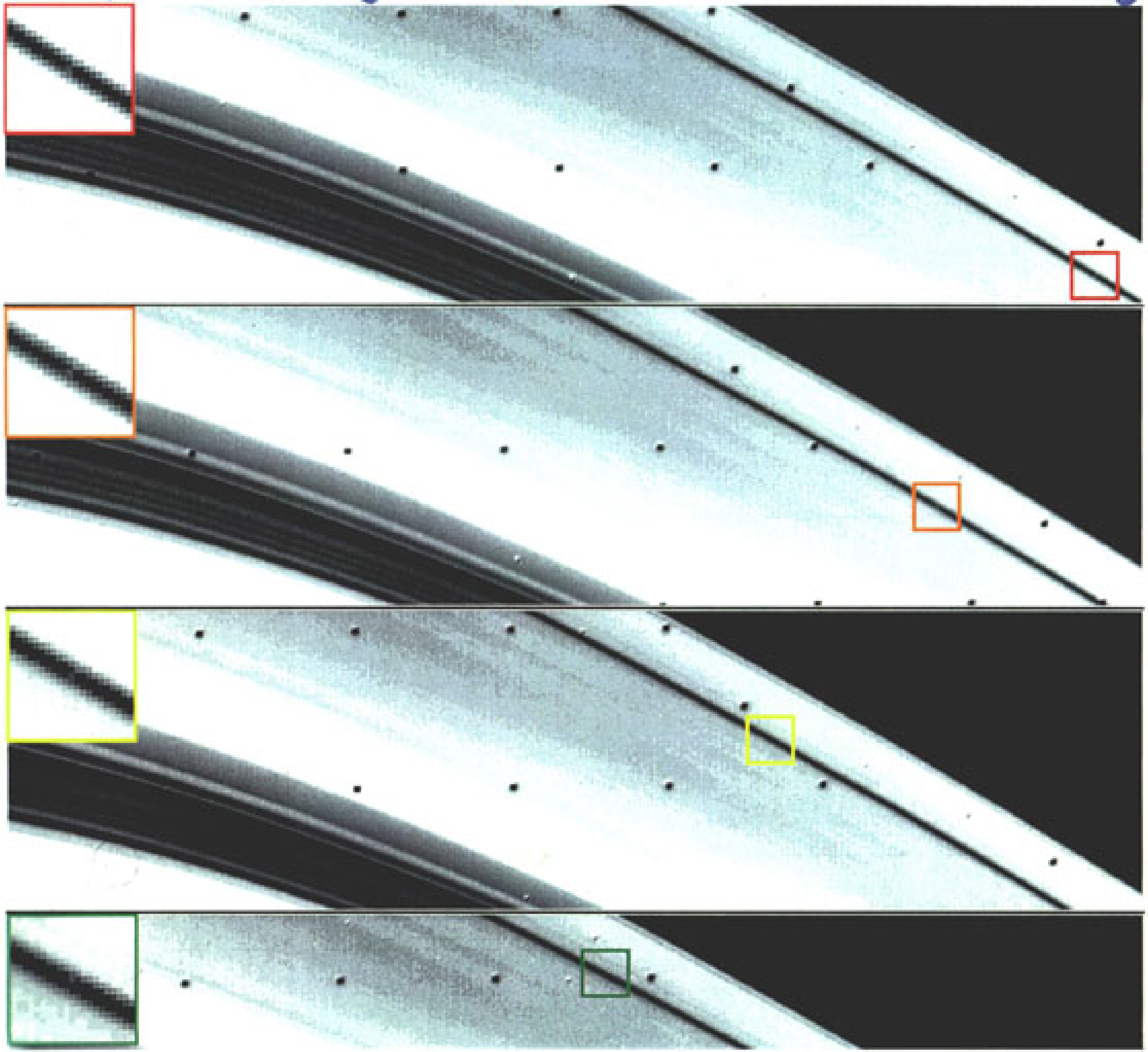
- 1. Planet's ability to "absorb" gas ($\uparrow$ as M_p $\uparrow$)
- 2. Supply limit (Bondi rate) when $\rho_{neb} << \rho_{neb}$(minimum mass)

B. Growth ends when gas is expelled

- 1. By star/disk/external
- 2. Planet's gravitational torques

C. Gas accretion leads to mergers/ejections

Gap-clearing moonlet in Saturn's Rings



Showalter (1991)

TECHNIQUES FOR FINDING EXTRASOLAR PLANETS

Method	Yield	Mass Limit	Status
Pulsar Timing	$m/M\ ;\ \tau$	Lunar	Successful
Radial Velocity	$m\ \sin i\ ;\ \tau$	Uranus	Successful
Astrometry	$m\ ;\ \tau$		
Ground: Telescope		Jupiter	Ongoing
Ground: Interferometer		sub-Jupiter	In development
Space: Interferometer		Uranus	Being studied
Transit Photometry	$A\ ;\ \tau$		
Ground		Saturn	Ongoing
Space		Venus	Proposed (Kepler)
Reflection Photometry: Space	albedo $A\ ;\ \tau$	Saturn	Proposed (Kepler)
Microlensing:	$f(m,M,r,D_S,D_L)$	sub-Uranus	Pilot projects
Direct Imaging	albedo $A\ ;\ \tau$		
Ground		Saturn	In development
Space		Earth	Being studied

Distribution of Extrasolar Planets

1 - 2% of G & K stars have planets more massive than Saturn within 0.1 AU.

~ 5% of G & K stars have planets more than twice as massive as Jupiter within 2 AU.
Some of these planets have very eccentric orbits.

One planet dominates (over a large range in *a*).

At least a few % of stars have Jupiter-like companions (0.5 - 2 M_J, 4 AU < *a* < 10 AU), but > 20% do not.

★Formation of Extrasolar Planets

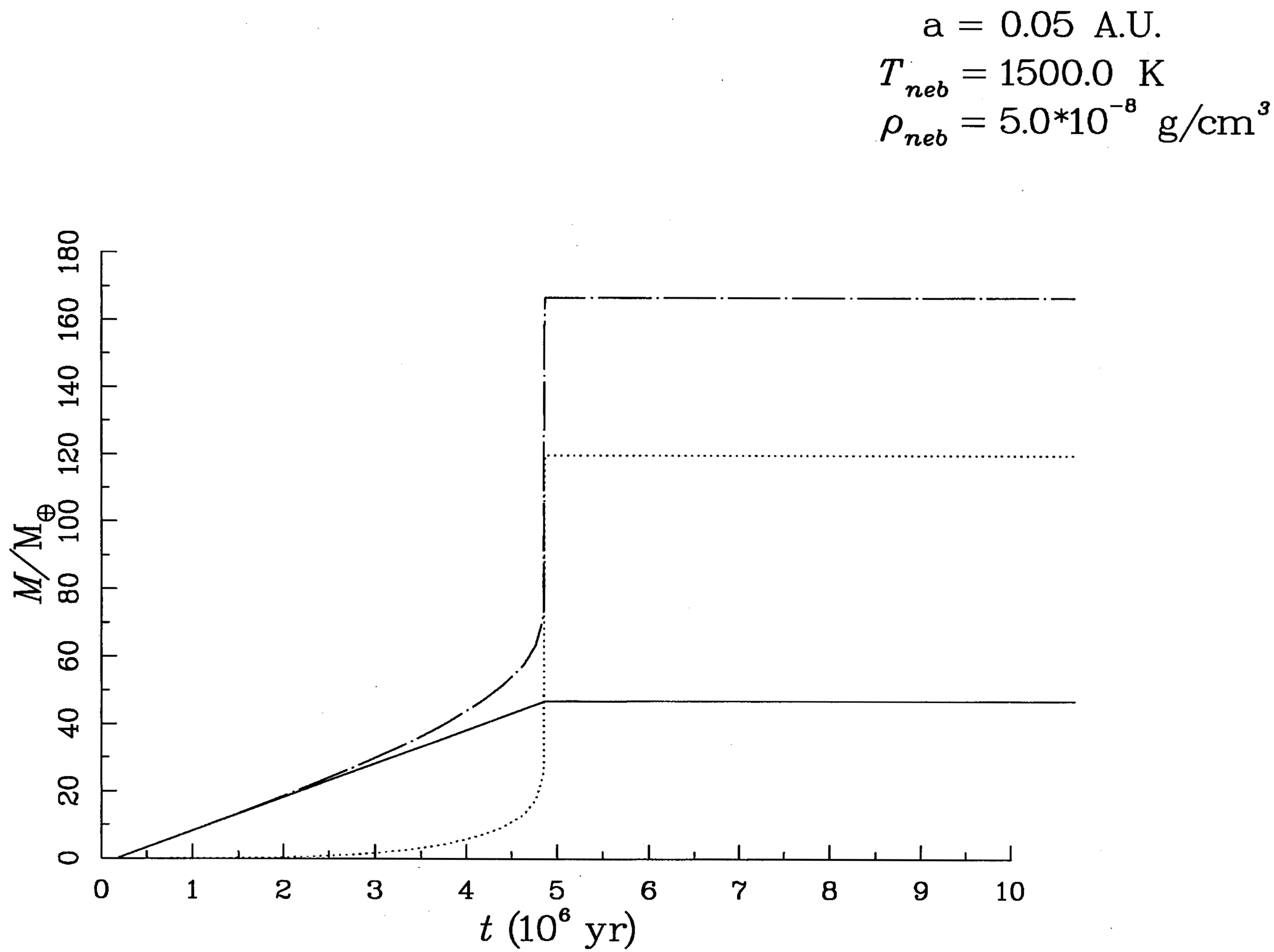
Low mass binary companions/Disk instabilities (all)

In-situ planet growth (small *e*: 47 UMa, 51 Peg?)

Planetary Migration (small *a*: 51 Peg, τ Boo)

Chaotic Scattering (large *e*:16 Cyg B, Gl 876)

Secular Resonances (binary star: 16 Cyg B)


a = 0.05 A.U.
T_{neb} = 1500.0 K
ρ_{neb} = $5.0*10^{-8}$ g/cm^3
$M/M_\oplus$
0
20
40
60
80
100
120
140
160
180
0
1
2
3
4
5
6
7
8
9
10
t (10^6 yr)

Orbital Evolution

<u>Torque between planet and disk</u> <u>(during planet formation epoch)</u>

No Gap: Migration relative to disk (Type I)

Gap: Planet moves with local disk (Type II)

Time scales shorter near star $\Rightarrow$

Need stopping mechanism (star's tide; gap; mass transfer)

Planetesimal-induced migration (massive disk required)

<u>Mutual scattering</u> <u>(can occur well after planet formation epoch)</u>

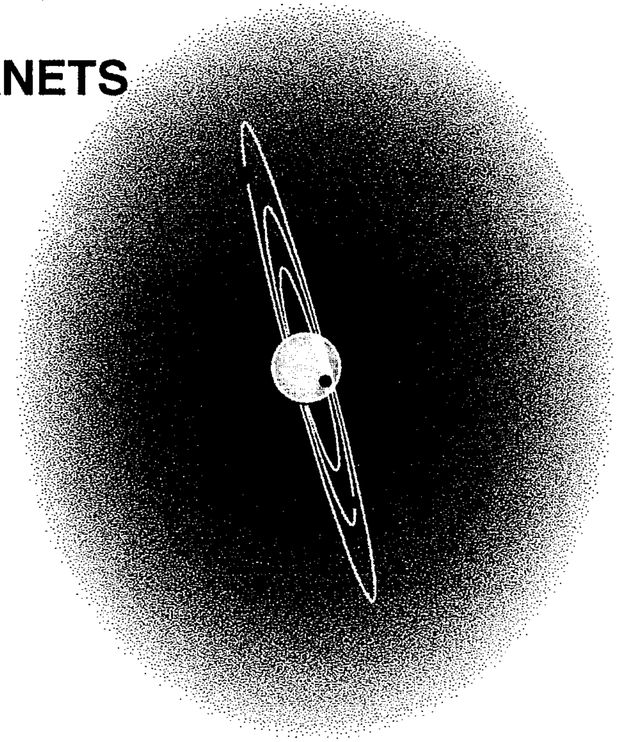
Produces eccentric orbits

Planets well-separated

Some planets ejected

Binary companion can also perturb orbits

PHOTOMETRIC DETECTION OF EXTRASOLAR PLANETS

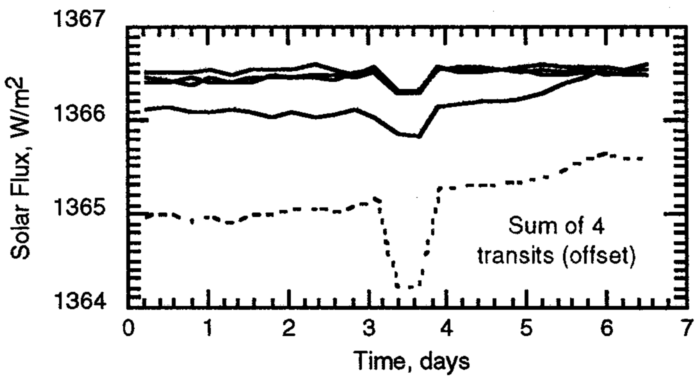


Transit of an Earth-sized planet:

Duration 4 -16 hours;

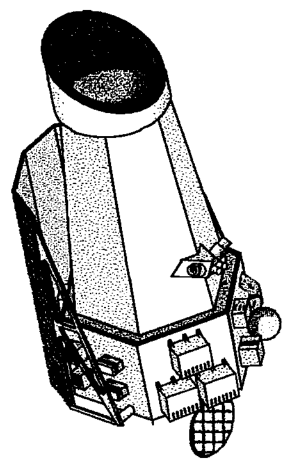
Brightness change ~1:12,000;

Inclination 89°-90°.



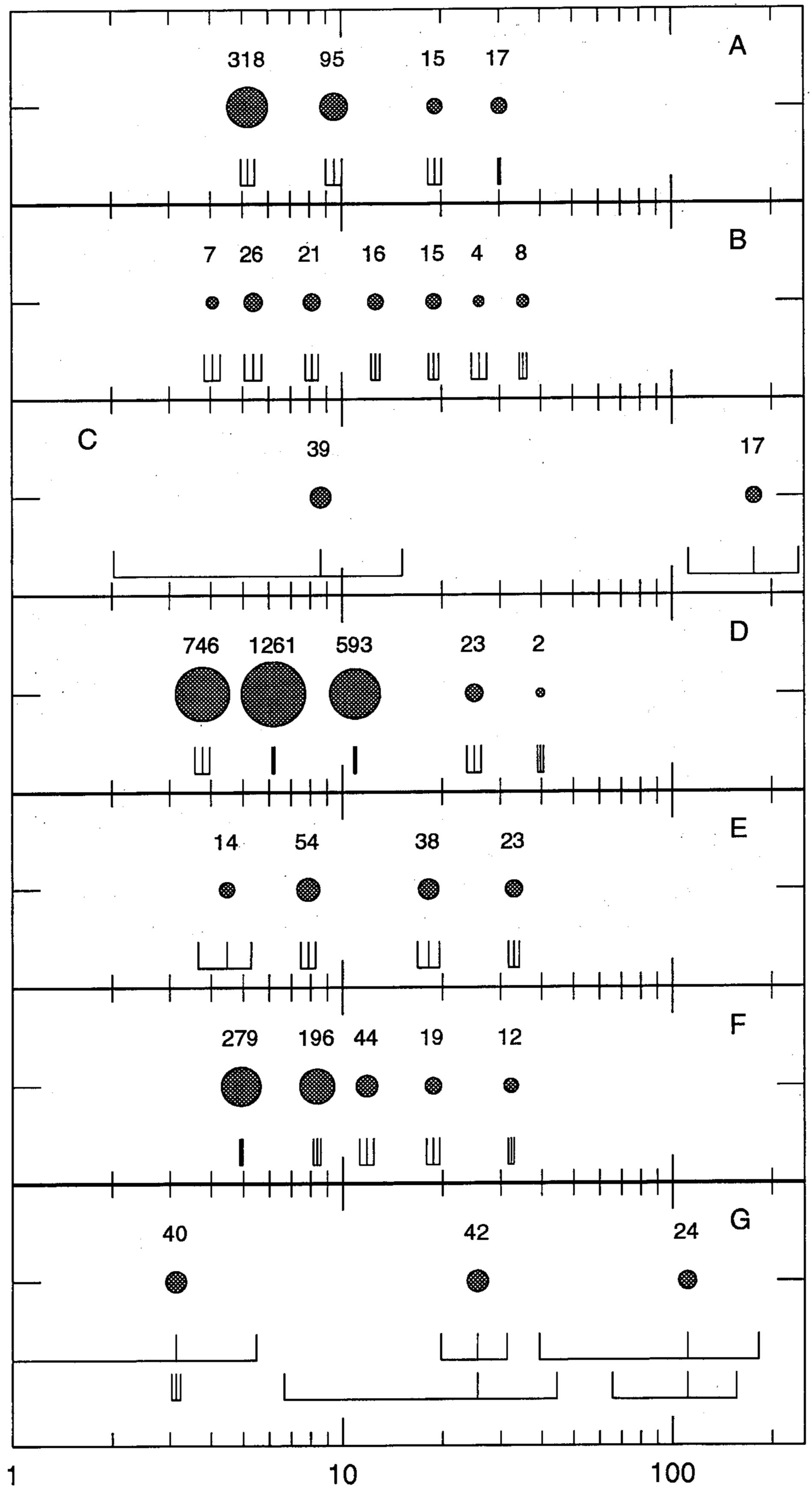
Two transits of a star provide an orbital period.

Three or more transits confirm a discovery.



Brightness change and star's size => Planet's size.

Orbital period and star's mass => Orbital size and temperature.


A
318
95
15
17
B
7
26
21
16
15
4
8
C
39
17
D
746
1261
593
23
2
E
14
54
38
23
F
279
196
44
19
12
G
40
42
24
1
10
100

⚓Constraints From Extrasolar Planets⚓

Radial velocities give only *M*sin*i*, *a*, *e*.

Statistics available only for LARGE planets NEAR stars.
These planets observed around ~ 5% of stars in sample.

⇒ Most planetary systems *may* be like Solar System.

BUT

Giant planets may take too long to form

$\Rightarrow$ *Systems with only small planets.*

Giant planets may migrate into stars

$\Rightarrow$ *Terrestrial planets may be destroyed.*

Unstable planetary systems may form

$\Rightarrow$ *Ejections, mergers, eccentric orbits.*

Conclusions

The *Planetesimal Hypothesis/Core-Instability Model* provides a viable explanation of giant planet formation.

Terrestrial planets likely form around most (single) stars, *Jovian planets* less common.

Giant planets form most "easily" in ice condensation zone, but also elsewhere.

Giant planet *orbits* can be altered by disk, other planets or binary companions.